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PUNCHING FAILURE OF REINFORCED CONCRETE SLABS SUBJECTED TO HARD MISSILE IMPACT: SIMULATION OF INFLUENCE OF SLAB THICKNESS & SHEAR REINFORCEMENT IN LS-DYNA

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ABSTRACT

The IMPACT project is organized by VTT Technical Research Centre in Espoo (Finland). The fourth phase of this project, for the **NE**w **R**esearch **E**ffort in the **I**mpact **D**omain (IMPACT IV – NEREID), was launched in 2019. IMPACT IV – NEREID focuses on the influence of the test scaling on the various structural response phenomena (including bending, punching, as well as combined bending and punching response) studied in the previous three phases of the IMPACT project. It also aims at obtaining further experimental data exploring new scenarios of impact loading on reinforced concrete structures.

The project IMPACT IV – NEREID includes a series of so-called ITP (Increased slab Thickness Punching) tests with reinforced concrete slabs subjected to impacts of non-deformable missiles. The ITP tests have the objective to investigate the effect of the slab thickness increase, as well as of the presence of shear reinforcement on the punching capacities of the reinforced concrete slabs subjected to impact loading and their perforation limit.

The capability of finite element models to predict the impact response of reinforced concrete slabs with increased thicknesses is assessed by comparing the results of numerical simulations to the experimental data. The calculated results showed a good agreement with the experimental values for the “hard impact” tests, which were carried out successfully. However, for the tests, where the missile demonstrated unpredictable loading characteristics (deformation and splitting), the test results cannot be reproduced reliably and thus the experimental data cannot be used to verify the simulations.

INTRODUCTION

VTT and STUK (Finnish radiation and nuclear safety authority) started the IMPACT project in 2003. Foreign partners joined the project in the follow-up phases IMPACT I – III (2006 – 2018). VTT continues to organize the fourth project phase (IMPACT IV – NEREID), which is funded by several institutions including the Swiss Nuclear Safety Inspectorate (ENSI).

The aim of the IMPACT project is to perform experimental and numerical studies of impact loading on reinforced concrete structures. In order to validate the test results from the previous IMPACT phases, the test scaling effects, as well as new impact scenarios are studied. This paper investigates the influence of the increased slab thicknesses and the presence of the shear reinforcement on the punching capacities of the reinforced concrete slabs subjected to impacts of non-deformable projectiles. The capability of finite element models to predict the impact response of reinforced concrete slabs is discussed by comparing the results of numerical simulations to the measurements of the increased thickness punching (ITP) tests. This paper outlines the contribution of the ENSI and its consultant Basler and Hofmann AG in numerical simulation of ITP tests carried out as a part of IMPACT IV – NEREID project.

EXPERIMENTS

Three reinforced concrete square-shaped (2.1 m × 2.1 m) slabs, tests ITP1, ITP2, and ITP4, were subjected to impacts of 47.5 kg non-deformable missiles as outlined in Table 1. The punching impact tests (P1 – P3) carried out in IRIS 2010 benchmark project (Vepsä et al. 2012) were chosen as the reference tests for these newly carried out experiments. The objective of these tests was to study the punching failure and the perforation limit of slabs subjected to impact loading, by increasing their thicknesses from 250 mm in IRIS P1-P3, to 300 mm in ITP1, and 350 mm in ITP2 and ITP4. Test ITP4 contained shear reinforcement in the form of T-headed bars. These experiments were carried out at VTT in 2019.

The missiles of tests ITP2 and ITP4, consisting of a solid stainless steel front cap and a stainless steel tube with lightweight concrete filling, did not behave as intended (as hard projectiles). Substantial missile cracking/splitting and buckling, as well as some concrete infill loss were observed during these tests. Therefore, the tests (newly designated as ITP2R and ITP4R) were repeated in 2021 with an improved missile shape in order to promote hard impacts; see "new missile" in figures 1 and 2. The significantly stiffer new missiles have a continuously towards the front increasing wall thickness. The total mass of 47.5 kg, the diameter of 168.3 mm, as well as the pipe thickness of 12.5 mm correspond to the old missile type used in the reference tests IRIS P1 – P3, as well as in ITP1, IT2, and ITP4.

Table 1: Data of the ITP series tests (IMPACT IV-NEREID)

	IRIS P1 / P2 / P3	ITP1	ITP2 / ITP2R / ITP2RR	ITP4 / ITP4R/ ITP4RR
Slab Thickness [mm]	250	300	350	350
Bending Reinforcement	Ø 10 @ 90 mm c/c both directions and faces(8.73 cm^2/m)			
Shear Reinforcement	-	-	-	Ø 12 @ 90 mm c/c ($34.9\ cm^2/m^2$)
Concrete Compressive Strength [MPa]	67.1 / 64.7 / 64.9	59	60.5 / 64.5 / 45.3	61 / 63.6 / 45.3
Impact Velocity [m/s]	136 / 135 / 136.5	137.8	149.1 / 162.3 / 144	151.8 / 144 / 156.1
Residual Velocity [m/s]	34 / 45 / 36	25	0 / 48 / 35	0 / 0 / 29

The repeated test ITP2R with an intended target impact velocity of 160 m/s was successfully concluded by achieving a tested impact velocity of 162 m/s. However, the same intended target impact velocity was not achieved in the test ITP4R. The measured tested velocity of this test was only 144 m/s (see Table 1). For this reason and in addition to the unplanned presence of fibres in the concrete of these two slabs, it was decided to repeat the two experiments for a second time as tests ITP2RR and ITP4RR. These tests did not go according to plan either, as the concrete strength did not reach the desired order of magnitude of the previous tests in this series as listed in the Table 1.

Figure 1. Test setup (left) and deformed projectiles after tests (right)

NUMERICAL MODEL

Method and Assumptions

Three-dimensional finite element analyses of ITP tests are carried out using an explicit integration method in the LS-DYNA software (R 11.0) for modelling hard missile impacts on reinforced concrete slabs.

The basic assumption for all three models is that the target remains stationary. It is assumed that the steel support structure provides enough stiffness so that large target deformations are not expected. Therefore, the supporting frame is not modelled.

A perfect bond is assumed between the concrete and the reinforcement. Numerical simulations are carried out by fully modelling the impacting missile.

Element Types and Material Models

The slabs are represented by eight-noded hexahedron constant stress solid elements for the concrete and two-noded beam elements for the reinforcement. The heads of the T-headed shear reinforcement in the tests ITP4R and ITP4RR were modelled using shell elements.

The pipes of the old missiles are modelled by shell elements and their concrete fillings by solid elements. Solid elements are used for modelling both the steel and the concrete filling for the newly designed missiles. Supporting steel bars, placed between the slab and its supporting frame, are modelled using solid elements. The slabs concrete elements are represented by a mesh size of approximately 15 mm × 15 mm × 15 mm.

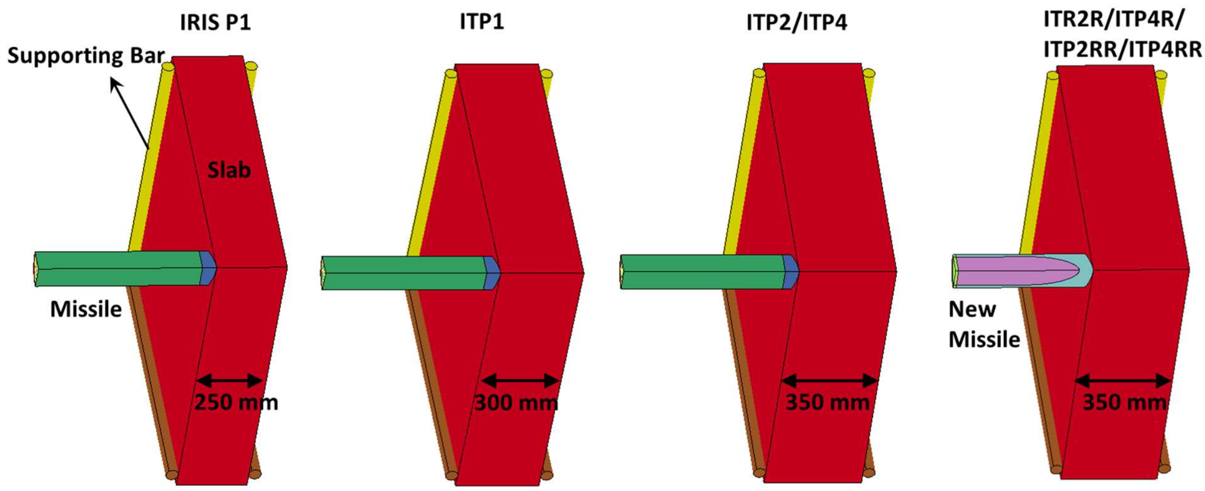

Figure 2. Finite element model geometry

The continuous surface cap model (material model 159) of LS-DYNA is used for the concrete. This material model allows for definition of an erosion criterion for the concrete. An eroding constant of ERODE=1.2 is used based on the calibration with the reference tests, which allows erosion of the damaged concrete elements when the maximum principle strain exceeds 20%. The compressive strength of concrete for the three tests is taken from experiments on concrete cylinders according to the Table 1. Figure 3 shows the uniaxial state stress-strain relationships for concrete and reinforcing steel.

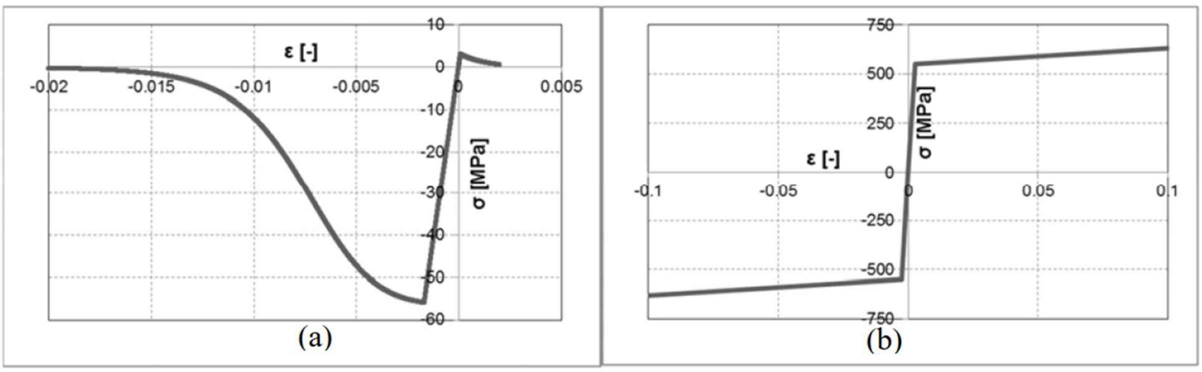

Figure 3. Stress-strain relationship for: (a) concrete, and (b) reinforcing steel

The constitutive model for the longitudinal bars and stirrups is bilinear with strain hardening. The reinforcement erodes when the strain in the beam elements exceeds 10%. The concrete and reinforcement elements are assumed to have a perfect bond where the concrete solid elements are connected to the reinforcement beam elements at nodal points. The same nodes are defined for the reinforcement and the concrete where they are in contact with each other. The impacting missile and the supporting system are modelled using bilinear models (yield strength of 355 MPa) with strain hardening.

Loading and Support Conditions

The initial position of the impacting missile is defined at the surface of the slab. The missile is then subjected to a predefined initial velocity. Contact surfaces are defined between the missile and the reinforced concrete slab, as well as between the concrete slab and the supporting bars. The outer nodal points of the supporting bar elements are defined by fixed boundary conditions. Due to symmetry, only quarters of the test bodies are modelled.

PREDICTED RESULTS AND COMPARISON

Missile Response

The calculated impact load time history, defined as the contact forces between the missile and the target is plotted against the loading function, derived by a simplified approximation for the test ITP4R, in Figure 4. The simplified approximation of the impact time history is based on the projectile penetration depth obtained according to Kennedy 1976. This formula, also known as Modified National Defence Research Committee (NDRC) formula is based on the theory of penetration and can be used to describe a non-deformable projectile impact into concrete. The impact force, at any time step, is derived as a function of the time dependent penetration.

The durations of impact and the maximum load values obtained from the finite element analyses and the simplified method correlate reasonably well, as can be seen from this comparison. However, the average load value obtained from the simplified approximation based on Kennedys' penetration formula is higher since the same impulse is acting on a shorter duration.

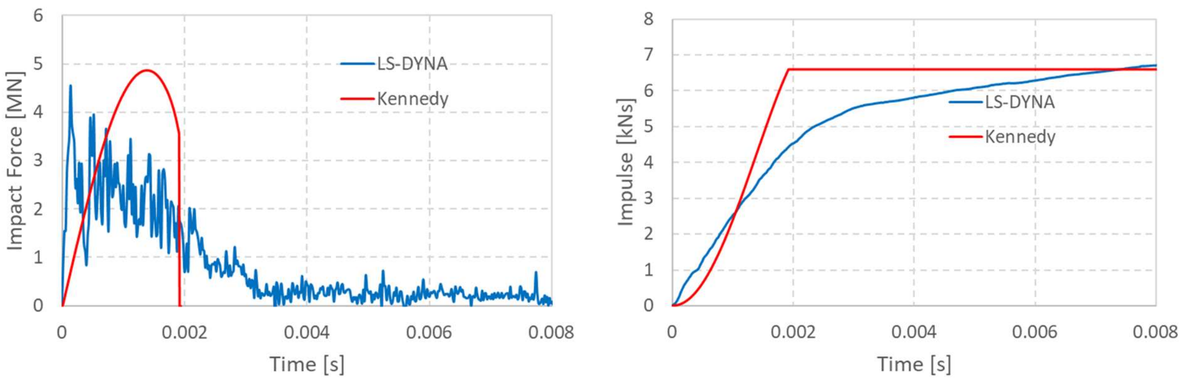

Figure 4: Comparison of impact load time histories and their impulses for test ITP4R

Perforation Predictions and Residual Velocities

All three almost identical punching tests of IRIS 2010 perforated their slab with relatively high residual velocities of 34-45 m/s, which confirms the repeatability of these tests. Numerical simulations of the IRIS punching tests lead to perforations with residual velocities of 44 – 63 m/s depending on the set of parameters used for defining erosion, as well as for the friction between the contacting surfaces of the missiles and the slabs. These velocities slightly overestimate the measured values.

Varying the erosion and friction parameters for the test ITP1, blind numerical analyses predicted perforation in all cases with a value of residual velocity ranging between 21 to 29 m/s. The predicted value corresponded very well to the measured residual velocity of 25 m/s for this test where the missile damage and thus the undesirable missile energy dissipation was not extensive.

The blind numerical analyses, assuming a rigid missile, predicted perforation with residual velocities of about 27 m/s for both ITP2 and ITP4 tests. However, due to the unplanned high dissipation of energy through missile deformation, splitting, and loss of some concrete infill, the forces transmitted to the slab were lower than expected and no clear perforation was observed in these two tests. Test ITP2 was near perforation since the missile was only held back through the bending reinforcement. A calibration calculation of ITP2 by adjusting the material properties of the missile resulted still in a perforation, but the calculated residual velocity decreased considerably to 10 m/s since some deformation in missile could be simulated. Due to the additional rupture/splitting, as well as the loss of the missiles' concrete filling, which cannot be realistically simulated, no further calibrations were performed. Therefore, the test results could only be used to a limited extent to verify the calculation models.

The results of the blind calculations for ITP2R and ITP4R are compared to the experimentally measured residual velocities in Figure 5. For the test ITP2R with the actual impact velocity of 162.3 m/s, the calculated residual velocity of 39 m/s corresponds reasonably well with the measured residual velocity of 48 m/s. The numerical analysis of the test ITP4R did not predict perforation for the tested impact velocity of 144.1 m/s similar to the test outcome. The calculated penetration depth of the projectile into the slab of 240 mm, however, slightly overestimates the measured penetration of 150 mm for this test. The calculated perforation limits for ITP2R and ITP4R, obtained by gradually varying the impact velocity, are 140 m/s and 145 m/s, respectively (Figure 5 right).

The calculated residual velocity for the test ITP2RR was 40 m/s, which corresponds well with the measured value of 35 m/s. For the test ITP4RR, the calculated velocity of 42 m/s slightly overestimates the measured value of 29 m/s. It can be concluded that the calculations performed generally well in predicting the punching response of the slab for these tests.

Test	Calc. Res. Velocity [m/s]	Meas. Res. Velocity [m/s]
IRIS P1-3	44 – 63	34-45
ITP1	21 – 29	25
ITP2	10	0
ITP4	-	0
ITP2R	39	48
ITP4R	0	0
ITP2RR	40	35
ITP4RR	42	29

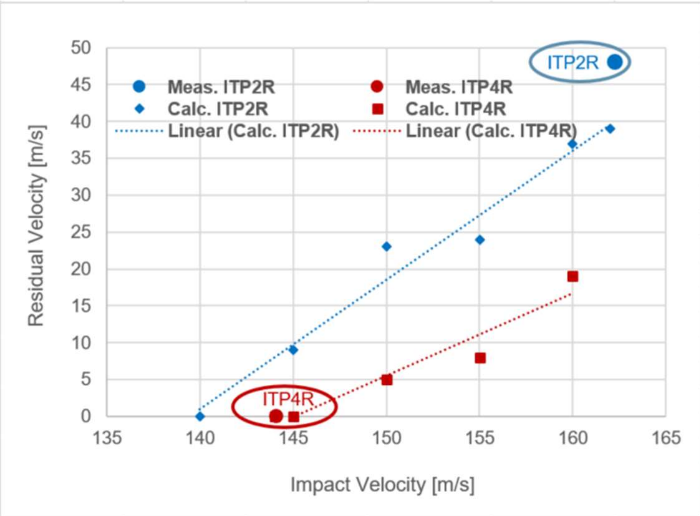

Figure 5: Comparison of the residual velocities (left) and perforation limits for ITP2R and ITP4R (right)

It can clearly be seen, by comparing the residual velocities of the test ITP1 to the reference tests IRIS P1-P3, that for the similar impact velocities, the residual velocity (both measured and calculated) decreases once the slab thickness is increased from 250 mm to 350 mm. Additionally, the test ITP2RR (350 mm thick slab) with considerably higher impact velocity than the tests IRIS P1-P3 (250 mm thick slab) led to comparable residual velocities for these two tests after perforation. These comparisons confirm the increase of the perforation limit while increasing the slab thickness. Since the impact velocities are not similar it is not easy to quantify the increase of the punching capacity (perforation limit) based on the experimental outcome. However, the perforation (ballistic) limit of the slabs can be estimated analytically using Kar's method (Kar 1979) using the following equation.

$$V_R = \sqrt{\frac{{V_i}^2 - {V_p}^2}{1 + \frac{M_c}{M_m}}}$$

Where, V_R is the residual velocity of the missile after impact (m/s), V_i is the impact velocity (m/s), V_p is the perforation or ballistic limit, M_c is the mass of the spalled concrete (kg), and M_m is the missile mass in kg.

Using the experimentally obtained values of spalling masses and residual velocities, the perforation limit obtained applying Kar's formula (Kar, 1979) is listed in the Table 2. It should be noted that the measurement of the residual velocity, especially for the experiments that were far from perforation limit is not very accurate and thus the values of the perforation limit obtained here may not be representative for all the cases. However, it is possible to confirm from this comparison that the perforation limit increases with increasing slab thickness.

Table 2: Perforation limits obtained using Kar's Formula

	IRIS P1	ITP1	ITP2R
Slab Thickness [mm]	250	300	350
Approximate mass of the spalled concrete M_c [kg]	120	180	136
Impact Velocity [m/s]	136	138	162
Residual Velocity [m/s]	34	25	48
Perforation (ballistic) limit [m/s]	**120**	**126**	**132**

Deflection Time Histories

Figure 6 shows the deflection time histories of the slabs at the location of sensor 1 (at 300 mm horizontal and 230 mm vertical distance from the slab center) at the impacted face of the slab. The results of the tests ITP2 and ITP4 are not shown in this figure since these tests were not performed successfully as mentioned earlier.

Deflections obtained from finite element models are in a good agreement with the measured data of the slabs without shear reinforcement (ITP1, IT2R, and ITP2RR). However, for tests ITP4R and IT4RR with shear reinforcement, the slab deflection is highly underestimated. This may imply too stiff modelling of these slabs. It may also correlate with the definition of the friction coefficient between the missile and the slab, which determines how much force is transferred during the tunneling process.

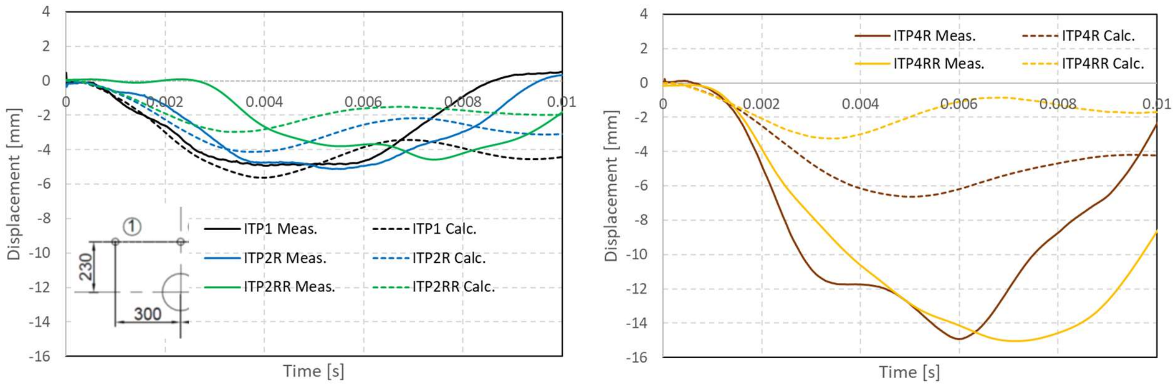

Figure 6: Deflection time histories of the sensor 1

Slab Damage

Figure 7 shows the cross sectional slab damages after the impact in comparison to the damage patterns after the test. The calculated punching cone patterns correspond to the experimental patterns observed in the cut section of the slabs.

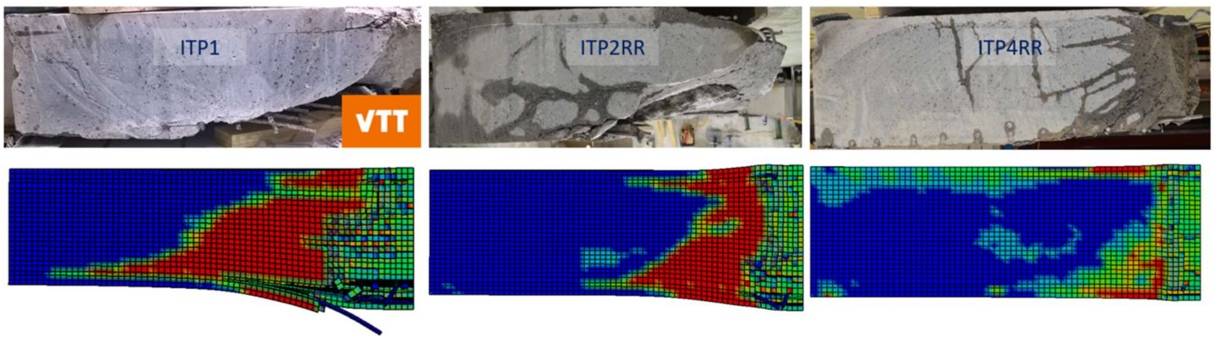

Figure 7: Slab damages for the tests ITP1, ITP2RR and ITP4RR, cross sections

Figure 8 shows the damage in the back side of the slabs after the impact (spalling and cracking) in comparison to the damage pattern after the test. The damage patterns correspond to the experimental spalling and cracking. However, the extent of damage is slightly underestimated for the tests ITP1 and IT2RR.

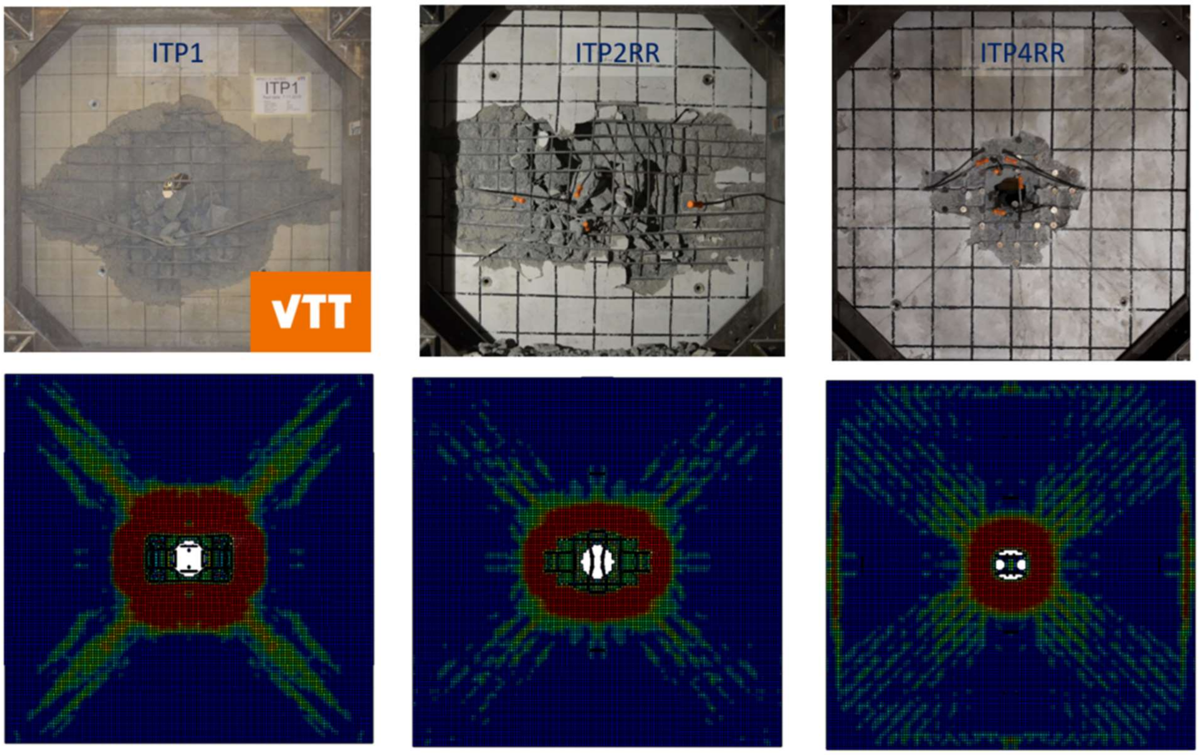

Figure 8: Slab damages for the tests ITP1, ITP2RR and ITP4RR, back view

CONCLUSION

Finite element analyses have been carried out for the prediction of increased slab thickness punching tests, which aim at exploring their capability to replicate the impact response of reinforced concrete slabs. The analyses, which were calibrated with the IRIS P1 test, predicted the perforation and the residual impact velocity of the missile very accurately for the test ITP1, ITP2R, ITP4R, ITP2RR, and ITP4RR. For the tests ITP2 and ITP4 the analyses overestimated the response of the slabs, where no experimental perforation was obtained. The main contributor for the discrepancy of the results is the unexpected missile response during these tests.

The calculated displacements were in a good agreement with the measured displacements for the tests ITP1, ITP2R, and ITP2RR. However, for the tests ITP4R and ITP4RR with the shear reinforcement the displacements were underestimated. The slab damage pattern (cracking and spalling) was predicted reasonably for these tests. The punching cone observed in the cut-section of the slabs matched with the contour of the numerically plotted concrete plastic strains.

The comparison of the experimental, numerical, and analytical results confirmed the increase in the perforation (ballistic) limit of the slabs while increasing their thicknesses from 250 mm, to 300 mm and 350 mm.

An objective of these experiments was to investigate the effect of the shear reinforcement on the perforation limit. This was only partially achieved. An effective comparison was not possible between tests

ITP2 and ITP4 due to the unplanned response of the missile. Additionally the impact velocities achieved during the tests IT2PR and ITP4R were not similar, which made it difficult to draw any conclusions from the experiments. However, the calculated perforation limits for ITP2R and ITP4R, obtained by gradually varying the impact velocity, were 140 m/s and 145 m/s, respectively, which confirms the effect of the shear reinforcement in increasing the perforation limit. Additionally, considering the significantly higher impact velocity of the test ITP4RR compared to the test ITP2RR, resulting (both experimentally and numerically) in almost identical residual velocity, it can clearly be concluded that the presence of the shear reinforcement increases the punching capacity in the case of hard impacts for these slabs.

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